Tailored laser beam shaping for efficient and accurate microstructuring

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Abstract

Large-area processing with high material removal rates by ultrashort pulsed (USP) lasers is coming into focus by the development of high-power USP laser systems. However, currently the bottleneck for high-rate production is given by slow and inefficient beam manipulation. On the one hand, slow beam deflection with regard to high pulse repetition rates leads to heat accumulation and shielding effects, on the other hand, a conventional focus cannot provide the optimum fluence due to the Gaussian intensity profile. In this paper, we emphasize on two approaches of dynamic laser beam shaping with liquid crystal on silicon spatial light modulation and acousto-optic beam shaping. Advantages and limitations of dynamic laser beam shaping with regard to USP laser material processing and methods for reducing the influence of speckle are discussed. Additionally, the influence of optics induced aberrations on speckle characteristics is evaluated. Laser material processing results are presented correlating the achieved structure quality with the simulated and measured beam quality. Experimental and analytical investigations show a certain fluence dependence of the necessary number of alternative holograms to realize homogeneous microstructures.

1 Introduction

An increase of productivity represents a significant challenge to transfer ultrashort pulsed (USP) laser based microstructuring processes into industrial application. The economic efficiency of processes such as laser based surface treatment of tools for embossing [1], printing applications [2] and scribing of solar cells [3] mainly depends on achievable ablation rates. The commercial availability of high-power USP laser systems potentially enables upscaling of the respective processing strategies, however, requires appropriate system technologies. The first straightforward approach is pursued by high repetition rates requiring fast

beam deflection [4]. Alternatively, using high pulse energies in combination with flat-top beam shaping or parallelization by multiple beams [5] also achieves high ablation rates. In this second approach, a laser pulse frequency in the multi-kHz range can be commonly used to prevent shielding effects by ejected material [6]. Furthermore, the usage of flat-top-shaped intensity distributions promises to be advantageous regarding high structure quality and ablation efficiency [7]. In contrast, a Gaussian shaped intensity distribution can be disadvantageous in several micromachining applications. Flanks of a Gaussian intensity distribution below the ablation threshold induce heat in the workpiece leading to heat affected zones (HAZ) which are undesired as, e.g., they lead to a lower electrical performance in manufacturing of solar cells [8]. The wear resistance of carbon-based coatings suffers from HAZ, too [9]. Furthermore, regions of high intensity which significantly exceed the ablation threshold can decrease ablation efficiency due to less energy efficient thermodynamic phase transitions [10]. Therefore, laser beam shaping of flat-top intensity distributions represents a promising approach to accelerate USP laser based micro-machining as well as to enhance the quality of the generated microstructures. Although, static beam shaping is sufficient to provide the mentioned benefits in most cases,

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system technologies and methods for beam shaping of flat-top profiles with flexible contours are highly relevant.

In this context, liquid crystal on silicon spatial light modulation (LCoS-SLM) and acousto-optic beam shaping (AOS) are addressed in this paper. Both methods enable flexible holographic beam shaping due to the local variation of the phase of the laser beam. LCoS-SLM is based on the individual manipulation of the refractive index of pixels of a liquid crystal display, while acousto-optic beam shaping (AOS) is based on a fast variation of an acoustic wave enabling a spatially dependent phase variation of laser beams. The AOS technology enables wavefront shaping [11] particularly for 3D nonlinear microscopy [12] and intensity profile shaping [13].

One major issue of holographic laser beam shaping is given by occurrence of speckle in the image plane of focusing optics which significantly reduces flat-top quality by strongly appearing intensity fluctuations. In digital holographic beam shaping speckle occurrence is caused by interference of adjacent waves of a pixel-wise discretized desired intensity distribution [14]. In common phase mask calculation algorithms, these adjacent pixels of the digital image plane representation have random phases [15]. Thus, stochastic interference and deviations from the desired pattern occur. As these intensity fluctuations can cause inhomogeneous material ablation and degrade structure quality, appropriate methods for efficient speckle reduction in flat-top beam shaping are necessary. A previously proposed approach for speckle reduction is based on averaging over time of the constructed image of a multiple shifted hologram or of different holograms [16]. Alternative methods enable speckle-suppression in the focus plane by either constraining the phase of the focal plane during hologram calculation [17] or by subsequent shaping of amplitude and phase with two separate spatial light modulators [18].

In this paper, different influences on characteristics of time-averaged speckle patterns and the effect on microstructuring are investigated. Therefore, time-averaging techniques

are applied for LCoS-SLM and AOS beam shaping of femtosecond laser pulses. The optics and the system dependent influences on beam quality are discussed and the relating influence of the number of averaged holograms is investigated by simulation and experiment. The effect of aberrations is investigated by LCoS-SLM based beam shaping and a non-dispersion corrected AOS system allows to determine the effect of partial reduction of the coherence in holographic beam shaping. AOS is ideally suited to reduce coherence of broadband USP laser by introducing chromatic aberrations originated from off-axis deflection with large deflection angle. These aberrations result in an incoherent superposition and are advantageous regarding homogeneous structure depth in microstructuring experiments. Structuring experiments of stainless steel substrates are carried out to correlate the evaluated beam quality with structure quality parameters depending on the used laser fluence. The experimental results are compared to simulations of the ablated depth based on the logarithmic ablation law [19]. Based on the presented findings, the minimum number of holograms which has to be used to generate microstructures with homogeneous depth by femtosecond laser ablation can be estimated.

2 Experimental setup and methodology

2.1 Experimental setups

Performance of holographic flat-top beam shaping is evaluated by the optical setup shown in Fig. 1. For the sake of simplicity, folding-mirrors have been omitted. The laser beam of wavelength $\lambda = 1030$ nm emitted by the femtosecond fiber laser system (OneFive, Origami XP, pulse duration $\tau = 400$ fs) is adjusted in polarization and its diameter before manipulation by either the components of the LCoS-SLM setup (A) or the optics of the AOS setup (B).

Fig. 1 Scheme of the experimental setup for camera based evaluation and laser based microstructuring experiments of holographically shaped intensity distributions by LCoS-SLM (setup A) and AOS (setup B)

In setup A, a phase-only LCoS-SLM (Hamamatsu Photonics, X10468-03) is used with prior calibrating the specific optical response of the device according to [20] to ensure maximum diffraction efficiency. The laser beam is adjusted by a beam expander to a $1/e^2$ diameter of 7.8 mm and is reflected by the SLM at angle of incidence of 4.6° . The following 4f-optical setup consists of two identical lenses with 100 mm focal length (Thorlabs, LB1676-B) which image the Fourier plane (FP) at the LCoS-SLM into the entrance pupil of a typically used telecentric f-Theta lens for laser beam scanning with 82 mm focal length (Sill optic, S4LFT0082/328). The f-Theta lens focuses the phase modulated Gaussian laser beam leading to the desired distribution of the intensity in the image plane (IP). The intensity distribution is captured by a higher NA digital microscope (Edmund Optics, DIN 10×0.25 and IDS, UI-1220SE-M-GL).

In setup B the laser beam is expanded to 6.8 mm to meet the smaller aperture of the AOS. In this specific case, the AOS is a 2D-acousto-optic deflector (AOD, Brimrose, 2DS8-50-30-1030) consisting of two perpendicularly oriented TeO_2 crystals with an aperture of 8 mm which are operated by a pair of amplifiers (amp, Brimrose, PA-50-30-10-23-B1). The acoustic signals are sampled by a 2-channel arbitrary waveform generator (AWG, National Instruments, NI PXIe-5451). The synchronization is adjusted by a photodiode (PD, Thorlabs, PDA8A) and a delay generator (DG, Stanford Research Systems, DG645). The entrance pupil of the telecentric f-Theta lens is 32 mm in front of the surface of the first lens and is adjusted to be in between the two crystals.

2.2 Hologram calculation

The phase holograms used for beam shaping by the LCoS-SLM were calculated by the established Gerchberg–Saxton algorithm (GSA) [21]. The amplitude in the FP is defined as an ideal Gaussian and the initial phase distribution is chosen to be random. Each hologram is calculated with $i_{\text{GS}} = 50$ iterations of the GSA because the mean-square-error (MSE) of the desired amplitude stagnates for higher number of iterations. For the case of speckle-reduction by phase-constraining in the image plane, holograms are calculated by the Double-Constraint-Gerchberg–Saxton (DCGS) [17]. Here,

the constant phase in the signal domain of the reconstruction is set to π and the amplitude is constrained according to Chang et al. [17]. The used algorithm for calculating the two separate acoustic signals of the two-dimensional phase mask for AOS is described by Strauß et al. [22]. A more detailed version can be found in the supplementary material.

2.3 Material processing

Additionally to camera based beam quality evaluation, the stainless steel alloy AISI304 is processed with the presented setups. The sample surface is characterized and shows an initial roughness $S_a = 0.040 \pm 0.004 \mu\text{m}$ ($n=6$). The repetition rate is set to $f_p = 50 \text{ kHz}$. The total number of laser pulses $N_p = 1000$ was used while the number of pulses per hologram $N_{p/H}$ is varied for the applied flat-tops, where each is calculated with a different initial phase distribution aiming at the same desired intensity. After laser machining the samples are cleaned for 3 min in an ultrasonic bath with isopropanol.

2.4 Simulation of the intensity distribution

The complex field of the wave consisting of the Gaussian intensity distribution of the laser beam and the relevant phase hologram in FP is Fourier transformed to calculate the amplitude and intensity distribution in the image plane (IP). The complex field in FP is zero-padded by factor 4 of the initial phase hologram resolution to increase resolution of the intensity distribution for modelling the impact of high spatial frequencies. Optionally, a variation of the phase hologram is included to evaluate aberrations induced by any optics. Therefore, defined aberrations of varied strength a are added to the shaped wavefront by the addition of the phase hologram and the phase of the distorted wavefront described by the Zernike polynomials given in Table 1. The chosen polynomials for $a=0.35$ overestimate the polynomials received by ZEMAX simulations of the 4f-setup and telecentric f-Theta lens of setup A shown in Fig. 1. Reasons of aberrations can be aberrations of the laser raw beam, lateral misalignment of the laser beam axis and the hologram center and aberrations by the imaging system. Thus, the assumed Zernike polynomials according to Table 1 should represent a realistic case of aberrations induced by the whole optical

Table 1 Aberrations induced by 4f-setup and f-Theta lens simulated in ZEMAX and used values for calculation

Noll index j	Strength a	1	2	3	4	5	6	7	8	9	10	11	12	13
	($\cong$ RMS)													
ZEMAX	0.016	−0.013	−0.002	−0.002	0.008	0.005	0.005	−0.001	0.001	0.000	0.000	0.012	0.000	0.000
Value	0.35	0.000	0.000	0.000	0.000	0.112	−0.031	0.062	−0.140	−0.160	−0.028	−0.172	0.050	−0.164
Value	1.00	0.000	0.000	0.000	0.000	0.321	−0.088	0.176	−0.401	−0.457	−0.079	−0.492	0.144	−0.469

setup. Additionally, significantly higher aberrations are simulated by $a = 1.0$. In the ZEMAX simulation the laser beam is described according to experimental system parameters.

2.5 Simulation of the structure topography

The resulting intensity distribution in IP is used to calculate the ablation depth t_{abl} according to Eq. (1) [19], where κ is the energy penetration depth, N_p the number of laser pulses, F the mean fluence in the flat-top and F_{th} the threshold fluence for ablation [19]:

$$t_{abl} = \kappa \cdot N_p \cdot \ln\left(\frac{F}{F_{th}}\right) \quad (1)$$

The material dependent parameters $\kappa = 5.0$ nm and $F_{th} = 0.05$ J/cm² are experimentally determined according to the zero-damage-method. For this purpose, craters are generated with a Gaussian intensity distribution and $N_p = 100$ for different fluences. The measured depths per pulse are plotted over the logarithmic scaled fluences, so that the slope and the intercept at the x -axis indicate penetration depth κ and ablation threshold F_{th} according to Eq. (1).

2.6 Evaluation of beam and structure quality

Flat-tops are captured by the imaging optics, while the topography of the squared microstructures is acquired with a confocal laser scanning microscope (LSM) LEXT4000 (Olympus). The quality is quantified by the speckle contrast SC and the flatness factor FLF according to the international standard of DIN EN ISO 13694 [23]. SC and FLF are the normalized standard deviation and the maximum over the mean intensity, respectively. These values are calculated from the acquired data from the inner dotted region, highlighted in Fig. 2a.

The structure quality is quantified by the normalized standard deviation of the depth (comparable to SC) of a

40×40 μm area in the middle of the quadratic structure (dotted line in Fig. 2b). To characterize the dimensional accuracy the width and the length of the structure are measured at 20 equidistant profiles.

3 Results and discussion

The usage of speckle-reduction methods for efficient and accurate digital holographic beam shaping and microstructuring requires knowledge of the influences on the beam quality and the effect of the beam quality on material removal. Therefore, appearance of speckle is experimentally and theoretically investigated depending on the system technology for beam shaping and used optics enclosing aberrations. In case of time-averaging methods, the system dependent minimum number of holograms for sufficient flat-top homogeneity is determined. Differences of the beam quality between LCoS-SLM- and AOS-based beam shaping are discussed. For speckle-reduction by phase-constraint calculated holograms the effect of aberrations on beam quality is also investigated. The influence of experimentally and analytically time-averaged speckle patterns on structure quality is discussed.

3.1 Optical performance of speckle reduction by time-averaging

The experimentally reconstructed and acquired flat-top intensity distribution of single holograms by LCoS-SLM shows strong speckle (Fig. 3a) occurrence. This speckle noise reduces with an increasing number of added alternative holograms (Fig. 3a). Accordingly, FLF and SC of the examined squared flat-top increase and decrease, respectively, with a higher number of added holograms (Fig. 3b). Additionally, the curve showing the dependence of SC on the number of holograms N reveals that it

Fig. 2 **a** Camera assessed intensity distribution and **b** measured topography, the evaluated areas are marked

Fig. 3 **a** LCoS-SLM shaped flat-top intensity distributions which are added by an increasing number of holograms N , **b** beam quality parameters for shown experimental and simulated flat-tops and **c** simulated flat-tops with aberration strength $a=0.35$

declines approximately proportional to $1/\sqrt{N}$ according to the fit function $SC(N) = [SC(N=1) - SC(N \rightarrow \infty)] \times N^{-c} + SC(N \rightarrow \infty)$. The reduction can be justified by the apparently stochastically uniform distribution of speckles within the flat-top acquired from uncorrelated initial random phase intensity distribution for each alternative hologram N [11]. However, appearing speckle are not completely stochastically uniform distributed as the experimentally achieved data for SC decline exponentially with $c=0.69$ and converge to a minimum different from zero. Therefore, speckle occurrence seems to have preferred direction which can be seen for $N=100$ added holograms. There, vertical flat-top edges show some superelevation. In the presented experimental investigations, this reduction leads to stagnating FLF and SC after $N=36$ added holograms. Here, we define that these parameters stagnate when the actual change of both parameters by an additional hologram is less than 0.5%.

As the flat-top intensity distributions for $N=1$ and $N=50$ of additionally aberrated alternative holograms (Fig. 3c) are similar to the flat-tops shown in Fig. 3a, the existing aberrations of the used experimental setup are predominant. The simulation of the intensity distribution according to

the procedure in Chap. 2.4 confirms the experimental findings. In general, the beam quality of flat-tops reduces with increasing aberrations, but even the comparatively strong simulated aberrations of $a=1.0$ lead to only slight growth of SC after averaging (Fig. 4b).

The speckle pattern for $a=1.0$ and $N=1$ appears similar to the experimentally acquired intensity distribution and the trend as well as absolute level of both curves of SC coincide well. Thus, we assume that the used setup induces significant aberrations. The effect of aberrations on SC of experimentally as well as theoretically obtained flat-tops is lower for multiple added holograms than for a single hologram. The difference ΔSC between exemplary SC values for $a=0.0$ and $a=0.35$ aberrations amounts to -0.031 and -0.042 for a single measured and simulated flat-top, respectively. Compared to this, ΔSC for the same strengths of aberrations for $N=50$ holograms is about -0.002 and -0.015 . Furthermore, it is obvious that the point of stagnation of speckle contrast remains constant independent of the assumed aberrations (Fig. 4b). Correspondingly, aberrations have a relevant influence on appearance of speckle in digital holographic beam shaping but they are smoothed by

Fig. 4 Calculated **a** intensity distributions and **b** quality parameters resulting from $N=1$ and $N=50$ with different strength a of defined aberrations. (For the sake of clarity, standard deviations are not shown.)

time-averaging nearly independent of the strength of aberrations due to its stochastic distribution.

Acousto-optic beam shaping with its inherent chromatic aberrations from off-axis deflection with large deflection angle enables an improvement of the beam quality parameters compared to the LCoS-SLM created flat-tops. The speckle pattern has lower spatial frequencies and a stronger smoothing effect of the added holograms is measured for AOS. This is caused by the chromatic aberrations of AOS reducing optical resolution. According to the above-mentioned fit function the improvement of camera-based assessed beam quality is less than 0.5% for more than $N=12$ holograms (Fig. 5a, b). At this number of holograms *FLF* and *SC* are found to be 0.87 and 0.06. This higher decrease with $c=2.34$ and the lower stationary state of *SC* compared to LCoS-SLM must be reasoned in the chromatic aberrations of the non-dispersion corrected AOS. This leads also to lower lateral accuracy of the AOS shaped intensity distributions, which is already evident from the focal spot (Fig. 5c).

3.2 Influences on speckle-reduction by phase constraints and diffraction efficiency

An additional approach to reduce speckle is investigated by constraining the phase distribution in the image plane of the focusing optics. The evaluation of the flat-top shaped

by a single DCGS-based hologram displayed on LCoS-SLM (Fig. 6a) reveals $SC=0.30$ (Fig. 6b) which is similar to *SC* of the flat-top of $N=5$ added holograms (Fig. 3b). The intensity distribution is significantly affected by the strength of aberrations according to the simulation of the aberrated flat-top. Strong aberrations seem to be induced by the optical setup because *SC* of the measured flat-top and the simulated flat-top with $a=1.0$ are similar. In this case, the simulated intensity distribution appears similar to the measured one as can be seen in Fig. 6a. Superelevation of the flat-top edges as well as significant waviness appears. Significant noise surrounding the desired flat-top and high intensity of the non-diffracted zeroth order are the main disadvantages of holographic beam shaping with phase constraints. Consequently, the measured diffraction efficiency of holograms calculated by DCGS is only 10.7% compared to standard Gerchberg-Saxton algorithm holograms with 68.7%. Compared to this, the diffraction efficiency of the AOS is about 32.2%. This seems to be low, but the high refresh rate and the resulting shorter dead time enable the usage of a higher number of laser pulses per time, which is important for the application of alternating phase masks. In comparison the efficiency of fixed diffractive optical elements is about 95% [7]. However, in contrast to fixed diffractive optical elements, dynamic beam shaping enables flexible adaption of shape

Fig. 5 **a** Measured intensity distributions, **b** quality parameters from $N=1$ and $N=100$ of the calculated and measured intensity distributions, **c** chromatically aberrated focal spot after two axial deflections at an acoustic frequency of 50 MHz

Fig. 6 **a** Flat-top intensity distributions of the same phase mask hologram measured by camera and received by simulation with added different strengths of aberrations a and **b** beam quality parameters of the shown single flat-top profiles

and dimensions of profiles which is especially necessary in the development of material removal processes.

For applications requiring high beam quality, DCGS algorithms may be feasible and should not be ruled out. However, providing high beam quality by DCGS phase mask design is assumed to be disadvantageous for efficient material processing due to the low diffraction efficiency and optical systems with minimal aberration optimized for beam shaping applications are mostly not available to make use of. Thus, efficient and accurate micromachining can be achieved only by time-averaging methods. In accordance to this, in our further experimental evaluation, the threshold fluence for material removal would not be exceeded by DCGS-based hologram-shaped flat-tops due to low diffraction efficiency coupled with a maximum pulse energy of $E_{p,max} = 30 \mu\text{J}$ of the available femtosecond laser system. Therefore, microstructuring experiments are only carried out for time-averaging methods.

3.3 Influence of beam quality of time-averaged intensity distribution on structure quality

Standard deviation of width and length of the squared structures decreases with increasing number of added holograms (Fig. 7b, c) as does the SC(depth) of the measured structure depth. The trend of width and length as well as SC(depth) show that a stationary state with constant lateral dimensions and constant deviation (tolerance $< 2\%$) as well as stagnating SC(depth) (tolerance $< 0.5\%$) is achieved after $N = 50$ alternative holograms (Fig. 7a). With a higher mean fluence, a lower SC(depth) can be realized. The stagnated values of SC(depth) coincide well with the simulated values although simulation of SC(depth) reveals slightly faster convergence than the experiment. One possible reason for this difference for $1 < N < 30$ added holograms could be an influence of the incubation effect which is not included in the simulation. At

low pulse numbers incubation leads to a decreasing ablation threshold fluence with increasing pulse number. In our simulation, however, a fixed ablation threshold of $F_{th} = 0.05 \text{ J/cm}^2$ and an energy penetration depth $\kappa = 5.0 \text{ nm}$ were used representing parameter values for material irradiated by $N = 100$ pulses. The decreasing SC(depth) for increasing fluence can be explained caused by the logarithmic dependence of the ablation depth on the fluence [19]. The results based on the presented methods clearly show that the theoretical calculation of the intensity distribution and beam quality parameters enables the determination of necessary number of holograms which have to be applied for high microstructure quality.

These findings can be transferred to the results of AOS-based structuring, too. Deviation of lateral dimensions stagnates after $N = 35$. However, the speckle contrast of the depth still declines (Fig. 8b). The mean fluence of the square shaped by the AOS is about $F = 0.11 \text{ J/cm}^2$ which is slightly above the ablation threshold. Thus, low intensity speckle do not induce ablation while high intensity regions generate significant material removal. This difference of ablated depth leads to apparent deviation of the structure shape e.g. a non-squared shape for $N = 8$ (Fig. 8a). This discontinuous material removal induces delayed decay of SC(depth) for multiple holograms and is characterized by SC(depth) stagnating at $N \geq 64$ holograms.

4 Conclusion

Two promising approaches of flexible flat-top beam shaping for microstructuring purposes have been investigated regarding beam shape and microstructure quality of squared flat-top profiles. Appearing speckle can be smoothed by time-averaging of the intensity distribution for both technologies: LCoS-SLM- and AOS-based beam shaping. Stagnation of

Fig. 7 **a** LCoS-SLM based structures, **b** measured width and length as well as **(c)** measured and simulated fluctuation of the structure depth SC(depth) ($f_p = 50 \text{ kHz}$; $F_1 = 0.09 \text{ J/cm}^2$; $F_2 = 0.26 \text{ J/cm}^2$; $N_p = 1000$)

Fig. 8 **a** Topography and **b** measured widths, lengths and SC(depth) of AOS based structures ($f_p = 50$ kHz; $F = 0.11$ J/cm²; $N_p = 1000$)

homogeneity of flat-top profiles is achieved for $N=36$ and $N=12$ added holograms in LCoS-SLM and AOS beam shaping. Simulation results of LCoS-SLM-based flat-top profiles show that stagnation and absolute value of the speckle contrast are nearly independent from optical aberrations. Low speckle contrast as well as high shape accuracy can be achieved by speckle-reduction of flat-top profiles with constrained phase. However, beam quality of phase-constrained flat-tops is significantly affected by optical aberrations. The diffraction efficiency decreases nearly about one order of magnitude by constraining the phase compared to holograms calculated by standard GS algorithm. AOS beam shaping results show that chromatic aberrations can dramatically reduce speckle due to a partial reduction of the coherence. Unfortunately, occurring dispersion associated to chromatic aberrations decreases accuracy of the flat-top shape. Furthermore, coincidence of beam quality parameters of measured and simulated flat-top profiles enables the calculation of averaged intensity distribution. Thus, the necessary number of holograms for sufficient flat-top homogeneity can be determined by the presented method.

Microstructuring experiments reveal that lateral dimensions and their standard deviation of the ablated squared geometry also stagnate for more than 40 added holograms. In the case of LCoS-SLM based structuring, the fluctuation of the structure depth stagnates at a similar number of holograms where a smaller fluence leads to slower convergence and higher stagnating SC(depth) due to slightly and only locally exceeded ablation threshold. This effect seems to be the main reason for the delay of stagnation of SC(depth) towards $N > 64$ of squared structures which are generated by AOS beam shaping. Eventually, the presented method of subsequent simulation of the intensity distribution and structure geometry represents an experimentally evaluated, highly accurate procedure to calculate USP laser based microstructuring processes with time-averaged flat-top profiles.

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