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# ANISOTROPIC RESIDUAL STRESS MEASUREMENTS IN ADDITIVELY MANUFACTURED 316 STAINLESS STEEL PARTS

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## Abstract

Additive manufacturing (AM) using laser powder bed fusion (L-PBF) is increasingly used to produce complex parts for industries like aerospace and medical devices. The intrinsic characteristics of AM – layer-wise deposition and rapid thermal cycling – generate significant, anisotropic, residual stresses that can compromise part quality and performance. Recent studies highlight how these stresses are strongly influenced by process parameters and build orientation. X-ray diffraction (XRD) techniques, including  $\sin^2\psi$  and advanced two-dimensional approaches, have become the preferred methods for non-destructive, directionally resolved measurement of residual stress in AM metals. This review surveys advancements in XRD residual stress methods with a focus on the analysis of additively manufactured 316L stainless steel that has been post-treated by shot peening. Coordinated development of AM and shot peening underscores the importance of residual stress characterization to guide process optimization and improve the structural integrity of AM components across diverse industrial sectors.

## 1. Introduction

Additive manufacturing (AM) by laser powder bed fusion (L-PBF), has the potential to transform the landscape of high-performance metal component fabrication. This technology enables the realization of intricate geometries, reduces material waste, and allows for local property control in alloys such as stainless steel 316L, which is widely valued for its corrosion resistance and mechanical reliability [1, 2]. However, the very nature of AM—with its rapid, localized heating and cooling cycles and layer-wise deposition—leads to the buildup of residual stresses. These stresses are not only significant in magnitude but also anisotropic, meaning their distribution and intensity are highly dependent on factors like build orientation, scan strategy, and part geometry [1, 2, 3]. Such complexities pose challenges including part distortion, dimensional inaccuracy, and reduced fatigue performance. These challenges are barriers to industrial qualification—especially in critical applications such as aerospace, biomedical, and energy sectors [1, 2, 3, 4, 5].

Controlling residual stresses is essential for ensuring part performance and reliability. Non-destructive characterization methods, such as X-ray diffraction (XRD), provide required spatial and crystallographic resolution [4, 6] on a millimeter scale of scrutiny. Advances in XRD, including the  $\sin^2\psi$  and  $\cos\alpha$  techniques, now enable comprehensive mapping and analysis of these complex stress fields in modern AM applications [4, 5, 6, 7].

This paper reviews residual stress characterization in additive manufacturing and considers post-treatment shot peening as an approach to improve surface finish and residual stress states. The review summarizes state-of-the-art XRD techniques for non-destructive surface stress evaluation, focusing on anisotropic stress measurement. Goals include the coordination of AM process optimization with shot peening as a post-processing strategy to improve the

structural integrity and qualification of AM 316L components. Challenges inherent to peening of stainless steel 316L are discussed in context of preliminary findings of a research project studying peening of L-PBF 316L test pieces, “Surface Modification and Characterization of AM Parts” sponsored by the Center for Surface Engineering and Enhancement (CSEE) at Purdue.

## **2. Residual Stress in Additive Manufacturing: Mechanisms, Consequences, and Control**

Residual stress generation is a fundamental challenge in metal AM by L-PBF. During printing, the material is subjected to highly localized and transient thermal gradients caused by the rapid, layer-by-layer melting and solidification of metal powders [1, 2, 8]. In-plane, non-uniform thermal gradients are caused by the melt pool raster pattern. As each new layer is deposited, previously solidified regions are repeatedly reheated and may partially remelt, causing established stress fields to redistribute, relax, or intensify depending on process parameters such as laser power, scan strategy (the path and sequence of the laser), hatch spacing, scan speed, and build orientation [1, 2, 8]. This unique thermal history – far more severe than in conventional manufacturing – directly drives the development of complex, anisotropic residual stress fields that are characteristic of AM [1, 2].

The spatial distribution and magnitude of these stresses are strongly influenced by process design and part geometry. For example, “upskin”, or exposed top, surfaces experience rapid cooling and tend to develop tensile residual stresses, while “downskin”, or supported regions, cool more slowly and often accumulate compressive or heterogeneous stresses—especially near substrate or support interfaces [1, 8]. The choice of scan strategy is critical: Robinson et al. [1] demonstrated that alternating and rotated scan patterns can reduce peak tensile stress and improve flatness in L-PBF 316L compared to unidirectional scanning. Similarly, Ge et al. [8] found that grooved or optimized substrates promote more uniform heat dissipation and lead to lower residual stress in AM parts.

If left unaddressed, these anisotropic residual stresses can cause part distortion, warping, or cracking, and can significantly reduce fatigue life—posing serious risks for critical components in aerospace, biomedical, and energy sectors [1, 2, 4]. For instance, excessive tensile surface stresses in thin-walled or lattice AM structures are known to initiate premature fatigue cracks [4], while local stress concentrations near supports or nodes can limit service life.

Process interventions such as scan path alternation, build orientation adjustment, and support/substrate engineering can be leveraged to manage heat flow and minimize thermal gradients during fabrication [1, 8]. After building, post-processing techniques like heat treatment and shot peening have proven effective for redistributing or relieving residual stresses [3, 4, 6]. For example, Gundgire et al. [6] showed that a combination of 900°C heat treatment and severe shot peening resulted in deep compressive residual stresses and a refined near-surface microstructure, significantly improving fatigue performance in AM 316L.

The effectiveness of all these strategies depends on accurate residual stress measurement. Non-destructive X-ray diffraction (XRD) methods, including  $\sin^2\psi$  and  $\cos\alpha$ , are widely used to precisely map surface, and near-surface stress fields [5, 7]. For depth profiling of highly complex geometries, destructive techniques such as the contour method may be necessary. XRD methods have a limited penetration depth, so additional techniques, such as neutron diffraction or the contour method, may be required to fully characterize stress profiles through the part thickness—especially in thick or highly complex AM builds. This integrated measurement

approach ensures comprehensive understanding and effective qualification of critical AM components.

Table 1 highlights strategies to mitigate undesired residual stress in AM parts. An integrated approach combines process optimization, post-processing treatments, and advanced measurement techniques to ensure the quality and reliability of additively manufactured components.

*Table 1. Key Factors Influencing Residual Stress in L-PBF AM and Control Strategies*

<b>Factor / Parameter</b>	<b>Effect on Residual Stress</b>	<b>Example Control / Mitigation</b>	<b>Reference</b>
Scan Strategy	Alters heat distribution; affects anisotropy	Alternating, rotated, or chequerboard patterns	[1]
Build Orientation	Dictates cooling rates, stress directionality	Orientation optimization	[1], [2]
Hatch Spacing & Scan Speed	Modulate cooling rates and thermal gradients	Adjust spacing/speed to reduce stress peaks	[1], [2]
Substrate/Support Design	Constrains or facilitates thermal contraction	Grooved/optimized substrates	[8]
Heat Treatment	Relieves bulk residual stress	Post-build annealing	[3], [6]
Shot Peening	Introduces compressive surface stress, refines microstructure	Severe shot peening	[3], [4], [6]
XRD Measurement	Enables mapping of surface/near-surface stresses	$\sin^2\psi$ , $\cos\alpha$ methods	[5], [7]

### 3. Shot Peening in AM 316L: Surface Modification and Residual Stress

Shot peening is often employed in the additive manufacturing (AM) of 316L stainless steel to treat surface gradients, and to introduce beneficial compressive residual stresses at and near the surface counteracting flaws and inherent tensile stresses induced by rapid thermal cycles during L-PBF. The process involves bombarding the surface with media, resulting in localized plastic deformation, grain refinement, and enhanced fatigue resistance. Compared to wrought materials, the response of AM surfaces to shot peening can vary due to differences in as-built roughness, microstructure, and existing anisotropic stress fields.

#### *Preliminary results from CSEE study, Surface Modification and Characterization of AM Parts*

Figures 1 and 2 show the surface morphology of both AM 316L and wrought 316L samples before and after shot peening. In the as-built condition, AM 316L surfaces exhibit higher roughness and irregularity than wrought 316L, reflecting the layer-wise nature of L-PBF. Shot peening produces a dimpled, matte texture in both materials, indicative of localized plastic deformation and near-surface grain refinement. The roughness increase is more pronounced in the wrought sample, highlighting the material-dependent response to peening. For AM, process parameters must be carefully optimized to avoid over-peening, which can amplify surface defects or compromise fine details – particularly in intricate geometries. Severe shot peening (SSP) applies higher intensity and/or longer duration to generate deeper, more stable compressive stress layers, but also carries greater risk of surface damage if not precisely controlled.

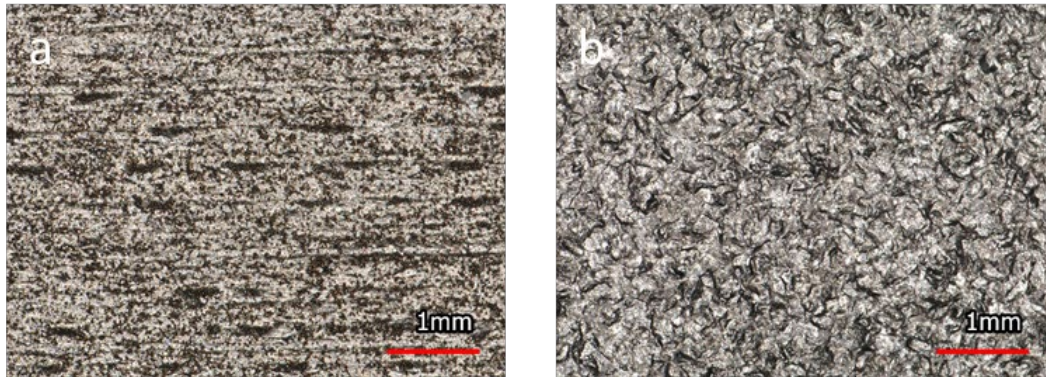


Figure 1. Optical images of AM 316L SS sample,  $t=1.33$  mm (a) As-built surface ( $Sa=4.81$   $\mu\text{m}$ ); (b) Surface after shot peening for 21s ( $Sa=23.74$   $\mu\text{m}$ )

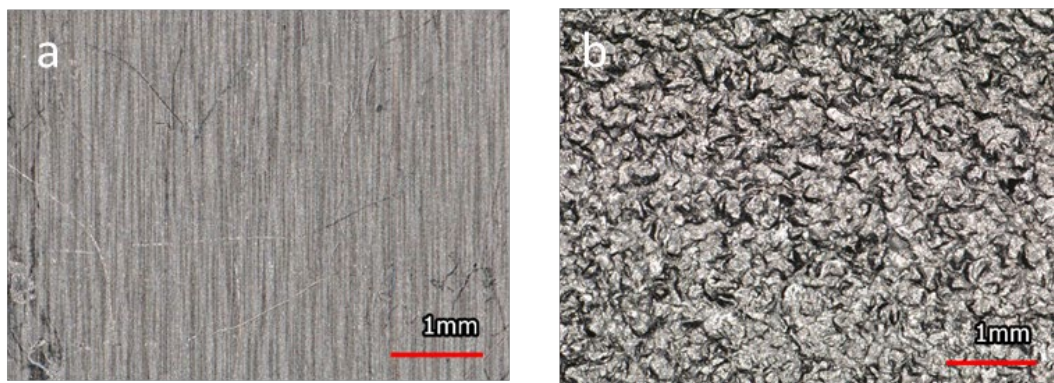


Figure 2. Optical images of Wrought 316L SS sample,  $t=1.33$  mm (a) Unpeened control sample ( $Sa=0.85$   $\mu\text{m}$ ); (b) Surface after shot peening for 13s ( $Sa=32.65$   $\mu\text{m}$ )

Almen strip testing is the legacy method of measuring the intensity of shot peening, and by inference, residual stress. Initial work on the CSEE AM-Peening study included peening 316L stainless steel surrogates of Almen strips. Specimens were cut from wrought stainless sheets and AM specimens built in a vertical-width orientation (Renishaw AM 400). Multiple thicknesses of both AM and wrought specimens were tested, as shown in Figure 3.

Specimens were attached to a standard Almen strip test fixture and peened over multiple passes on a linear drive traversing a well-controlled peening flux (ProcessMaster, Sentenso, Datelin, Germany). The peening treatment had a fixed flow rate of 2 kg/min with conditioned CW32 media (Toyo Seiko America, South Bend, IN, USA). Nozzle pressure was fixed at either 1 or 1.5 bar depending on the thickness,  $t$ , of the specimen treated, with resultant media velocity calibrated at 42 or 52 m/s, respectively. The media feed rate,  $\dot{M}$ , peening time,  $T$ , and media velocity,  $U$ , were used to calculate cumulative kinetic energy of peening:  $E = 0.5 \cdot \dot{M} \cdot T \cdot U^2$ , Table 2.

Table 2. Peening parameters at saturation using standard Almen strips, SAE J443 [9]

Almen	Pressure, bar	Velocity, m/s	Duration (s)	Energy, kJ	Almen Intensity
A-strip	1	42	8	0.24	13A
A-strip	1.5	52	5	0.23	16A
C-strip	1	42	7	0.21	4C
C-strip	1.5	52	4	0.18	5C

Arc height,  $h$ , was measured as a function of peening time. In Figure 3, the arc height was normalized to the thickness squared of the test strip, Appendix B, and the peening time was converted to kinetic energy. These scaling transitions enable the collapse of the data into two groups, one comprising wrought specimens (solid symbols), and the other AM specimens (open symbols). Both were fit to a 4-parameter saturation curve model [10], where the abscissa was converted from peening time to energy, and the ordinate was scaled using arc height and strip thickness,  $y = h \cdot t^2 = a(1 - \exp(-b \cdot E^c)) + d \cdot E$ , where  $b$  and  $c$  are common fit parameters across all specimens. Within each specimen group, parameters  $a$  and  $d$  were common, where  $a$  scales with thickness,  $a = a_0 \cdot t^n$ .

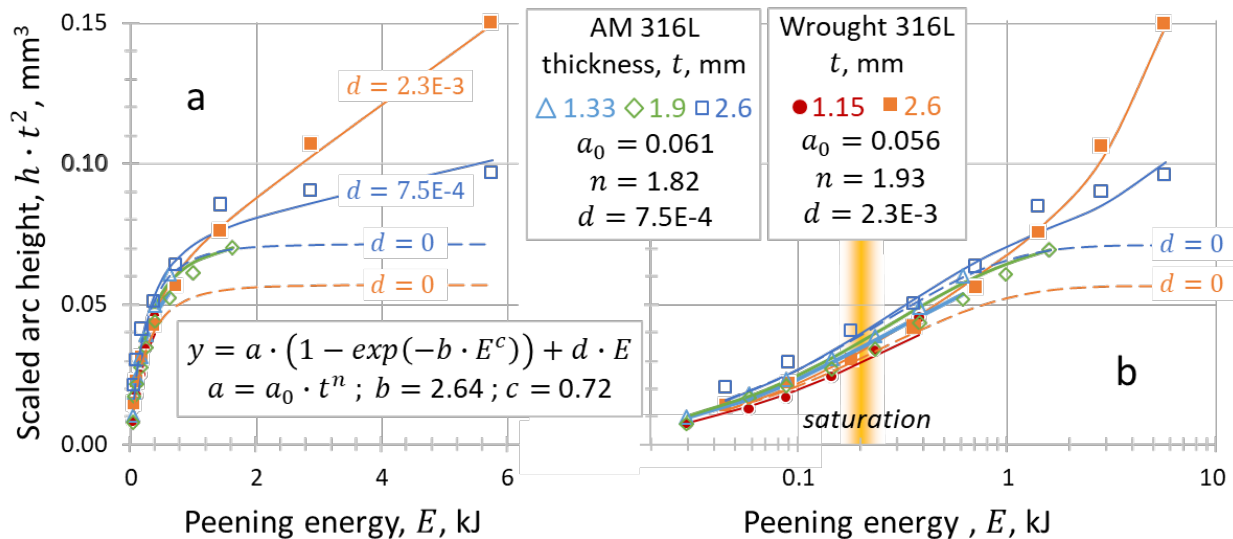


Figure 3. Scaled saturation plots for AM and wrought stainless steel samples of varying thickness. Dashed lines illustrate the effect of the linear deformation term,  $d$ , in severe peening. Geometric scaling of the abscissa (b) shows data near saturation per Table 2, (obtained using standard Almen strips),  $\sim 0.2$  kJ.

Notably, both stainless-steel specimen types show significant linear deformation suggesting plastic flow under severe peening conditions. The effect of the linear deformation parameter,  $d$ , shown in Figure 3 with the 2.6 mm thick strips, becomes most significant above saturation (saturation values are shown in Table 2).

Below and slightly above saturation, AM strips show marginally higher deformation, but wrought specimens have higher linear deformation in severe peening conditions. On one hand, the observation of plastic flow in both specimen types is not surprising considering the lower hardness of 316L compared to the peening media and/or 1070 spring steel used in standard

Almen strips. On the other hand, the observation of plastic flow highlights the challenge of peening of detailed AM parts, where excessive plastic deformation may compromise the integrity of detailed features. Preliminary data suggests a reasonable working window is possible with moderately excessive coverage, i.e., up to 3X saturation.

Current and future project work on AM peening utilizes high-resolution X-ray diffraction (XRD)—particularly the  $\sin^2\psi$  method—to provide spatially and directionally resolved maps of residual stress in both AM and wrought 316L. XRD measures the contribution between compressive stresses induced by peening and any residual tensile fields remaining from the build process [4, 5, 6]. When combined with advanced techniques such as the  $\cos\alpha$  method, XRD delivers a more complete picture of the stress state and anisotropy at or near the surface [5, 7]. This non-destructive characterization is essential for linking visible surface changes to real improvements in fatigue resistance and for optimizing peening parameters to maximize performance without damaging surface features [2, 4, 5, 6].

## 5. Recent Progress and Outlook

Recent literature demonstrates that advances in both AM process control and residual stress measurement are reshaping how engineers approach stress management in 316L stainless steel. Experimental studies have shown that tuning process parameters—including laser power, scan strategy, substrate and support design, and post-processing treatments like shot peening or heat treatment—can have a substantial impact on residual stress magnitude and spatial distribution [3, 5, 7, 8]. High-resolution X-ray diffraction (XRD) techniques, like  $\sin^2\psi$  and  $\cos\alpha$  methods, are increasingly paired with digital image analysis and automated, multi-orientation mapping, enabling comprehensive assessment of highly anisotropic microstructures [2, 4, 6, 7].

Despite significant progress, several technical challenges remain for fully optimizing residual stress management in AM 316L. On the process side, the layer-wise nature and rapid thermal cycling in L-PBF lead to complex, location-dependent stress fields and microstructures that can vary with build geometry and parameter selection. For XRD-based characterization, unique challenges include accurate calibration for strong crystallographic texture, managing the effects of surface roughness, and developing robust, automated measurement protocols that can reliably capture the spatially heterogeneous, anisotropic stress states typical of AM parts.

Another critical area of development is the integration of experimental measurement with predictive computational modeling. While finite element analysis (FEA) and process simulation have advanced significantly, their full potential is only realized when validated against experimental XRD data. Such hybrid experiment-model workflows are crucial for accurately simulating the interplay of thermal gradients, phase transformations, and mechanical constraints during the AM process – ultimately enabling data-driven process optimization and reducing reliance on trial-and-error.

Industrial implementation is now focusing on the deployment of automated, multi-orientation XRD systems, especially for safety-critical and high value applications. These systems enable rapid mapping of complex AM parts and provide the feedback necessary for closed-loop process control. At the same time, machine learning and advanced data analytics are increasingly being adopted to extract actionable insights from large, multi-modal measurement datasets.

This hybrid experiment–model workflow accelerates process optimization, reduces the reliance on costly trial-and-error experimentation, and enables rapid “first-time-right” manufacturing. Looking ahead, the synergy between automated, high-resolution XRD, robust computational modeling, and real-time process monitoring will form the backbone of industrial AM quality assurance—making reliable, data-driven production of complex metal parts achievable at scale.

*Table 3. Recent Advances, Challenges, and Future Directions in Residual Stress Management for AM 316L*

Category	Recent Advances	Remaining Challenges	Future Directions	References
Process Optimization	Tuning scan strategy, laser power, substrate/support design, post-processing	Complex interactions, lack of universal guidelines	Process-integrated control, machine learning	[3, 5, 7, 8]
Experimental Measurement	High-resolution XRD ( $\sin^2\psi$ , $\cos\alpha$ ), automated/multi-orientation mapping	Standardizing protocols, influence of surface roughness	In-situ XRD, real-time monitoring	[2, 4, 6, 7]
Computational Modeling	Coupling models with experimental validation (XRD, microstructure)	Model calibration/validation, integration w/ complex microstructures	Hybrid experiment-model workflows	[7]
Industrial Implementation	Multi-orientation XRD systems (e.g., Proto iXRD) for complex AM parts	Feedback/control integration, scale-up for industrial QA	Automation, integrated QA frameworks	[1, 2, 6]

## 6. Conclusions

Residual stress is a key challenge in the additive manufacturing of 316L stainless steel, directly impacting dimensional stability, fatigue performance, and part qualification. High-resolution XRD techniques now provide the spatial and directional insight needed to evaluate and optimize mitigation strategies.

Shot peening, when properly tailored, can transform surface tensile stresses into beneficial compressive layers, improving fatigue resistance in both AM and wrought 316L. XRD enables quantification of the depth, uniformity, and stability of these layers, ensuring process parameters are tuned for each geometry and application.

Future progress will rely on integrating XRD-based feedback with computational modeling and selective post-processing—such as heat treatment combined with peening—to deliver consistent, application-ready AM components. Ultimately, the synergy between advanced measurement and optimized shot peening will be critical for producing high-performance AM 316L parts that meet demanding industrial standards.

## Appendix A. X-ray Diffraction (XRD) for Residual Stress Analysis

X-ray diffraction (XRD) is the established technique for non-destructive residual stress measurement in metals, including 316L stainless steel produced by additive manufacturing (AM) [4, 6]. The core principle is simple: stress alters atomic spacing, producing detectable shifts in diffraction peaks as described by Bragg's law [4, 6]. This allows surface and near-surface residual stresses to be mapped with high spatial and directional resolution [2, 6].

What makes AM challenging for XRD is its microstructural complexity and anisotropy, due to rapid solidification, strong thermal gradients, and layer-wise construction. These features often result in pronounced crystallographic texture, spatial variations in grain size, and surface roughness, all of which demand careful calibration and interpretation in XRD measurements [2, 6, 8]. Determining the correct reference lattice spacing and accounting for texture are particularly important for accurate results in AM components.

The  $\sin^2\psi$  method is widely used for residual stress analysis. A series of scan angles distributed about  $\psi = 0$  is collected and peaks are analyzed to determine the shift in d-spacing, correlating to strain. The d-spacing is plotted versus  $\sin^2\psi$  to extract in-plane stress [2, 4]. This approach is highly sensitive to scan orientation; scanning over a range of orientations reveals the anisotropic stress states common in AM builds, including 3D stress tensor mapping [11].

The  $\cos\alpha$  method, enabled by 2D detectors, allows for rapid, full-ring data collection, supporting triaxial stress assessment and rapid mapping—even in geometrically complex or curved AM parts [4, 5].

In summary, XRD when applied with proper consideration of AM microstructures enables reliable, non-destructive characterization of residual stress. This supports both process optimization and qualification of advanced AM components.

## Appendix B. Beam Bending Analogy for Arc Height and Sample Thickness Relationship

A simplified beam bending model for the compression zone caused by peening provides a relationship for the arc height [12]. The arc height,  $h$ , is a ratio of the moment caused by the compressed zone divided by the resistance to the moment, equation A1. For standard Almen strips, the elastic modulus,  $Y$ , is known; for varying thickness,  $t$ , the second moment of area,  $I$ , depends on  $t^3$ . The moment,  $M$ , depends on the magnitude,  $\sigma$ , and depth,  $d$ , of the compression region. Plugging in all the known values, the relationship between the arc height and strip thickness is in equation A2. Since the thickness of the strip is much larger than the depth of the compression region, the overall relationship can be rewritten as equation A3 indicating that  $h * t^2$  is a reasonable approximation for normalizing arc heights by strip thickness so long as the ratio  $d/t$  is small.

$$h = \frac{\text{"Moment"}}{\text{"Resistance to moment"}} = 631 \frac{M}{IY} \quad (\text{equation A1})$$

$$h = \frac{3786\sigma d}{Yt^3} [t - d] \quad (\text{equation A2})$$

$$ht^2 = \frac{3786\sigma d}{Y} \left(1 - \frac{d}{t}\right) \quad (\text{equation A3})$$

## Acknowledgement

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